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Tunisia Renewable Energy Project

Systems Description Report

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TUNISIA RENEWABLE ENERGY PROJECT

SYSTEMS DESCRIPTION REPORT

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SUMMARY

In 1979, the Agency for International Development (AID) initiated a renewable energy project with the Government of Tunisia to develop an institutional capability to plan and institute renewable energy technologies in a rural area. The specific objective of the district energy applications subproject was to demonstrate solar and wind energy systems in a rural village setting. The NASA Lewis Research Center was asked by the AID Near East Bureau to manage and implement this subproject.

The village of Hammam Biadha Sud was selected as the demonstration site. The centerpiece of the demonstration project was a central 29-kW (peak) photovoltaic system used to provide power to the homes and to the commercial and institutional buildings in the village. Other systems are a solar-energy water heater and a solar space-heating system for the village clinic, a photovoltaic-powered drip irrigation system for open-field farming, a photovoltaic-powered drip irrigation for use in a greenhouse with thermal storage, a wind-powered pumping system also for use with a greenhouse with thermal storage, and a photovoltaic power system for a farmhouse.

As the result of a competitive procurement, NASA selected the Solar Power Corporation of Woburn, Massachusetts for the photovoltaic power systems. The systems were installed in early 1983. This report contains a detailed description of the project and of the equipment.

INTRODUCTION AND BACKGROUND

The objective of this renewable energy project with the Government of Tunisia (GOT) was to develop GOT institutional capability to plan and implement energy projects and to introduce and test renewable energy technologies in a rural area. The proposed assistance was aimed at enabling the GOT to devise plans that would lead to reduced dependency on fossil fuels and increase employment opportunities in rural areas. The AID Project Paper (Tunisia Renewable Energy Project, Project Paper, AID Project No. 664-0325, July 26, 1979), which provided the basis for the project, called for two complimentary activities: (1) the demonstration of renewable energy technologies in a rural agricultural setting and (2) various types of training to develop GOT capability to determine where, when, and how renewable energy could be applied to future needs.

As stated in reference 1, this cooperative energy assistance program was undertaken because of Tunisia's need to increase its fossil fuel reserves and/or find alternative energy sources to meet its development goals. In 20 to 30 years Tunisia will have to supply a minimum of 20 percent of its energy demands (i.e., approximately the total energy used in Tunisia in 1980) with

nonfossil or imported fuels. Also, rural electrification will not occur as rapidly as necessary solely through the central grid extension program. Meeting the rural electrification goals is considered necessary if Tunisia is to continue to make advances in economic and social development and stem the rising tide of migration to large cities. Finally, estimates indicated that Tunisia will become a net importer of fossil fuels by the late 1980's.

Based on these considerations, AID and the GOT executed a project grant agreement for the Renewable Energies Project (The Renewable Energies Project, Project Grant Agreement Between the Republic of Tunisia and the United States of America, AID Project No. 664-0325, Aug. 31, 1979). This agreement defined the goal and purpose of the project as follows:

The goal of the Project is to demonstrate the economic, social and technical value of alternative energy resources and technologies in assisting development and in improving the quality of life in Tunisia. The scope of the Project is limited to selected areas of the economy and should be viewed as a first step in implementation of alternative energy sources for Tunisia's social and economic development programs. This Project is designed to demonstrate the ability of alternative energy resources of sun and wind and alternative energy technologies to meet the energy needs of a village and its surrounding agricultural activities.

The specific purpose of the Project is to provide information to Tunisian decision-makers that will assist them in relating economic and social development to energy availability.

Also, the Project should increase the understanding of Tunisian decision-makers of the limits and value of selected renewable energy technologies in order to give them the capacity to decide when and where they should be introduced into rural economic development programs.

As stated above, the project was divided into two major subprojects: district energy applications (demonstrations) and training. This report deals only with the hardware demonstration phase and the focused training associated with the operation and maintenance of the solar technology equipment demonstrated.

DISTRICT ENERGY APPLICATIONS

The specific objective of the district energy applications subproject was to demonstrate the capability of solar and wind technology to perform work and supply the minimum electrical services necessary in a village and in rural agricultural settings. The village and district of Hassi El Frid, in south-central Tunisia, was originally chosen as the demonstration site but was later abandoned in favor of Hammam Biadha in north-central Tunisia. As originally envisioned, the subproject included the demonstration of eight technologies for four major applications. The first application combined photovoltaic water pumping with drip irrigation to obtain faster growth of young fruit trees in a semiarid region. This activity was aimed at achieving the most efficient use of the scarce water resource and identifying the potential benefits of controlled irrigation to arboriculture. The second application involved the use

of solar thermal technology in conjunction with a passive solar greenhouse to permit increased crop yields and an extension of the growing season. The third application concerned the pumping of water for traditional irrigating practices by methods that do not use fossil energy sources. The fourth application was to provide lighting to homes, institutions, and businesses, as well as heat for an infirmary. This application was based on the desire to minimize rural-urban migration and to concentrate people in villages in central Tunisia, the theory being that rural electrification would help make village life more attractive.

In a letter dated September 28, 1979 from Alfred D. White, Deputy Assistant Administrator for AID Near East Bureau to Donald A. Beattie, NASA Director of Energy Systems, the AID Near East Bureau requested that NASA manage the district energy applications portion of the Tunisia Renewable Energy Project (TREP). An existing Participating Agency Service Agreement (PASA No. NASA/DSB-5710-2-79, Amendment 3) between NASA and the AID Bureau for Development Support was amended to provide for the technical and management services of the NASA Lewis Research Center for this activity. NASA Lewis was given responsibility for implementing the district energy applications demonstrations (in conjunction with AID and the Societe Tunisienne de l'Electricite et du Gaz (STEG)), while AID retained responsibility for the training subproject.

PREIMPLEMENTATION PLANNING

In December 1979, personnel from Development Sciences, Inc. (DSI), the consulting contractor to AID for development of the project paper (Tunisia Renewable Energy Project, Final Report (Contract AID/DSAN-C-0039) Mar. 13, 1979), and NASA Lewis visited Tunisia to (1) establish working relationships with Tunisian counterparts in STEG, (2) hold initial coordination/organization meetings with AID/Tunisia, STEG, and other participating GOT ministries, and (3) conduct a preliminary site visit. The site for the proposed solar technology demonstrations was under review by the GOT. Because of a lack of sufficient well water for the agricultural aspects of the program at Hassi El Frid, the GOT was considering a new candidate site, Hammam Biadha Sud, located in north-central Tunisia (fig. 1). The results of the initial meetings and site visit are detailed by L.R. Scudder, et al. in Tunisia Renewable Energy Project (NASA Team Trip Report Dec. 10-19, 1979, NASA Terrestrial Photovoltaic Project Office Document 4210-050, NASA Lewis Research Center, Jan. 13, 1980). The major recommendations are summarized as follows:

- (1) That Hammam Biadha Sud be accepted as the demonstration site
- (2) That a revised project cost estimate be prepared by NASA based on the findings of the site visit and discussions with the AID and GOT officials
- (3) That a revised schedule, based on a new site and application mix, be accepted
- (4) That a detailed site evaluation be conducted by a team of solar and wind energy experts to further define the appropriate renewable energy applications, culminating in a system conceptual design for Hammam Biadha

- (5) That AID issue the necessary funding authorization to NASA to permit continuation of the project through the preimplementation phase

Recommendation 4 allowed AID to withhold a final decision on the project scope until a conceptual design and revised budget estimate were completed. Hammam Biadha was formally proposed by STEG and accepted by AID as the project site.

A detailed site inspection was conducted in February and March 1980 by a team of solar technology experts from both government and industry including U.S. and Tunisian participants. The information and data assimilated during the 2-week site visit resulted in the preparation of a conceptual design of the proposed solar demonstrations (Conceptual Design of Solar Technology Demonstrations at Hammam Biadha Sud, NASA Terrestrial Photovoltaic Project Office Document 4210-52, May 7, 1980). The conceptualized demonstrations at this stage consisted of nine applications grouped according to their function (agricultural or village). Agricultural applications are as follows:

- (1) Three solar greenhouses with thermal storage
- (2) A wind-powered water pump and drip irrigation system for one of the greenhouses
- (3) A photovoltaic (PV)-powered drip irrigation system for one of the greenhouses
- (4) A PV-powered drip irrigation system for one of the greenhouses and for an open field
- (5) A wind-powered drip irrigation system for an open field
- (6) A PV power system for domestic farm needs (one site)

Village applications are as follows:

- (1) A central PV system to service the residential, commercial, and public sectors of the village
- (2) A solar hot water system for the village clinic designed to provide a minimum of 200 liters of water per day at a minimum outlet temperature of 48 °C
- (3) A solar heating system designed to meet part of the space heating load of the clinic

Figure 2 shows the layout of Hammam Biadha Sud with systems locations.

Based on the results of the conceptual design study, it was determined that wind resources at Hammam Biadha were not sufficient to permit a meaningful wind electric application. However, water pumping using wind-powered mechanical pumps was included in the initial design concept. The agricultural applications consisted of solar and wind technologies used separately and in combinations on farms in the near vicinity of the village. The mix of proposed applications was based on the grant agreement requirements and subsequent discussions with STEG and the Ministry of Agriculture personnel. Some applications included technologies unfamiliar to the Hammam Biadha region (e.g., PV

power, drip irrigation, and greenhouses with thermal storage). Other technologies had been used in Tunisia, although not at Hammam Biadha (e.g., wind-powered water pumping). The demonstrations were designed to test the utility of certain alternative energy sources, under rural living conditions and agricultural practices which exist at Hammam Biadha, in order for the GOT to determine their impact on the social and economic development of the region.

The village applications were intended to demonstrate the feasibility of renewable energy sources to satisfy basic minimal energy needs of the village. Sizing and cost estimates for the PV system were based on an energy system which would accommodate the basic needs of the public and commercial sectors and that portion of the private sector which was anticipated to subscribe to the service initially. Based on STEG's experience with rural electrification, approximately 30 percent of the residents subscribe initially when power is made available. A PV power system designed to meet these conditions, as well as the case of 100-percent hookup by the private sector, was sized and cost-estimated for the conceptual design. The PV system sizing was based on a village load profile compiled from data obtained by personal interviews with every homeowner. Detailed descriptions of the various systems, along with the design criteria, assumptions, performance criteria, etc., are presented in the Conceptual Design of Solar Technology Demonstrations at Hammam Biadha Sud, which later served as the basis for the system specifications and statements-of-work for contract procurements.

PROJECT IMPLEMENTATION

NASA prepared a project implementation plan, which was approved in September 1980 (Implementation Plan for District Energy Subproject, NASA Terrestrial Photovoltaic Project Office Report 4210-053, NASA Lewis Research Center, Sept. 1980). The purpose of the plan was to establish the procedures for implementing the solar technology demonstrations and to identify the individual and combined responsibilities of all participants engaged in the project. The plan, in addition to covering the resources and manpower estimates, master schedule, and major milestones, also includes a description of each major implementation task. The interrelationship of the implementation tasks are depicted in the activity flow diagram shown in figure 3.

The final design, fabrication, testing, shipping, installation, and checkout of all the solar technology applications were accomplished through contracts with U.S. or Tunisian companies. NASA, with involvement of STEG, was responsible for the procurement of the PV power systems for the village, the farmhouse, and the drip irrigation applications and all other U.S.-procured systems and hardware. STEG, with technical assistance from NASA or NASA-provided consultants, was responsible for the procurement of all systems, hardware, and services from Tunisian contractors. To ensure compatibility of equipment and hardware, close coordination was maintained between NASA and STEG. To the extent possible, the two agencies participated jointly in the preparation of bidding documents and the evaluation and selection of contractors. A breakdown of the major system components by source (U.S. or Tunisian) is shown in table I.

STEG had lead responsibility for all site preparation and local construction, with technical assistance provided by NASA and/or NASA contractors and consultants. Wherever possible, local Tunisian materials, supplies, and labor

were employed. A minimum warranty period of 2 years was specified to cover all critical system components such as PV modules, batteries, inverters, etc., while STEG developed the experience and in-country support infrastructure to operate and maintain the systems.

BASELINE STUDY

In accordance with the AID project evaluation format, a baseline study of Hammam Biadha Sud was conducted by a STEG socioeconomist to (1) determine the economic and social characteristics of the project region, (2) predict the impact of the project on the population, and (3) determine the extent to which the project goals and objectives may be adopted by the affected inhabitants.

Toward this end, STEG conducted a survey of the following local and regional authorities: the Omda, the president of the party cell of Hammam Biadha, and the delegate of Krib (the principle city in the region). STEG also conducted interviews with the village residents to characterize their current lifestyle and working conditions/methods as well as to evaluate the village assets and needs. The baseline study encompassed two regions: (1) the scattered region, which consists of the plain surrounding the village (600 ha) and (2) the compact region represented by the village. The results of the study are presented in Etude Socio-Economique du Village de Hammam Biadha Sud (STEG, Tunisia, Tunisia, ER.HBS.01, Feb. 1980). The major conclusion of the study indicated that the site was suitable for the project based on the factors restated as follows:

(1) The needs in the domestic, commercial, and public sectors of the village were not too large for the scope of the proposed solar technology demonstrations.

(2) The village and surrounding farms provided the possibility of accomplishing the agricultural aspects of the project.

(3) The project was well received by the population and was "even called salutary."

(4) Electricity was desired by the villagers for the following functions in the order of decreasing priority: lighting, refrigeration, and television. Heating, ironing, and other high-energy applications were considered to be "superfluous luxuries" by the villagers, and hence the electricity demands would be within the range of the project.

(5) The authorities of the region and the population promised their support of the project.

In regard to the predicted impact of the project on the Tunisian rural lifestyle, the following information is paraphrased from Etude Socio-Economique du Village de Hammam Biadha Sud. The project participants (users) perceived an improvement in the quality of life through (1) better, more restful, cleaner lights, (2) more means of distraction and recreation via television, radio, music, etc., and (3) ability to make use of equipment necessary for more comfortable living conditions (especially the refrigerator).

Cultural and educational advantages cited as results of electricity included better lights, which would encourage school children to do homework in the evenings, and radio and television, which would increase the villagers' intellectual level by bringing them in closer contact with the rest of the country and the world. Television would also give children access to educational TV programs.

Since the villagers had been deprived of access to the national electrical network, the stand-alone solar energy systems would give them the satisfaction of being considered on an equal footing with the rest of the country. This equality was considered a social advantage by the study. A demographic advantage of electricity may be a lowering of the birth rate through television family planning programs.

In addition to the advantages cited, the project would create certain problems. One example was the problem of deciding who would benefit from the electricity and from the related applications and who would not benefit. Regardless of the selection criteria, there would be dissatisfaction. This problem was acute since solar energy systems are, by design, limited in energy output. The concept of limited energy was understood and accepted initially by the inhabitants. Everyone surveyed declared that "he was ready to make do with the minimum - enough to light one lamp and a television." Later, after people experience the advantages of electricity, the satisfaction with limited energy may be forgotten or rejected. The study proposed that there be continued educational programs aimed at maintaining the idea of strict energy conservation. The study also proposed that actions be taken to prevent a systematic urban extension, which would occur at the expense of both the project and the area agricultural production and which would encourage land speculation.

The Implementation Plan for District Energy Subproject calls for periodic followup visits to the project site to fully assess and evaluate the technical, social, and economic impacts of the project. STEG was given lead responsibility for the overall project evaluation process, and the reader is referred to that organization for any further information on the baseline study or followup evaluations (Chef de Projet-Energies Nouvelles, Department Planification et Etudes Generales, 38 Rue Kemal Ataturk, Tunisia, Tunisia).

CONTRACT PHASE

The contracting responsibilities of NASA and STEG are defined in the section PROJECT IMPLEMENTATION. Basically, NASA was responsible for all materials, equipment, and services procured from U.S. companies. STEG was responsible for all in-country procurements and all local construction and site preparation. All shipments of U.S.-procured goods were made under a government bill of lading. STEG, however, was responsible for clearing customs so that all shipments entered duty free in accordance with the project grant agreement.

NASA, through an open competitive procurement process, selected the Solar Power Corporation (SPC) of Woburn, Massachusetts for the photovoltaic power systems. The award was made on the basis of a cost share contract with a government option for a fixed-price, 2-year warranty service. The warranty service covered all major systems, subsystems, and components and is transferable with ownership of the equipment. TriSolarCorp of Bedford, Massachusetts

was the major subcontractor. Other subcontractors were Development Sciences, Inc. and ESSO Tunisie. The estimated contract period was 1 year; however, approximately 1-1/2 years elapsed between the effective date of contract and final acceptance of the systems in Tunisia. Shipping, custom clearance, and site preparation were major factors affecting the schedule.

A detailed description of the PV systems is presented in the following section.

SYSTEM DESCRIPTION

There are four photovoltaic (PV) power systems which supply electricity to Hammam Biadha Sud. These systems are designed to generate electricity for the basic village needs of lighting, refrigeration, and water pumping. The four systems include the central village, a remote farmhouse, a separate greenhouse, and an orchard of fruit trees at the farmhouse. Each of the systems has a separate PV power supply, the required set of auxiliary components, and a different set of electrical loads.

The village and farmhouse systems are similar in that they both contain storage batteries for backup supply and inverters to produce 220 V ac power. They differ basically only in their size and choice of specific components. The greenhouse and the orchard pumping systems are identical. Each of the four PV array systems is designed to provide the needed load based upon the available insolation by season and the efficiency of the PV array. The battery storage subsystems for the village and farmhouse are designed to provide electricity during the night and on cloudy days. In these two systems, the array and the battery bank are matched to complement and supplement each other through a power control system in order to provide appropriate electrical output over the year.

Village Power System

The village power system serves Hammam Biadha Sud's electrical needs for the domestic, commercial, and public sectors. The domestic sector includes 22 houses with varying electrical demands for lighting, refrigeration, and television. The commercial sector consists of two grocery stores, a mill, a coffee shop, and a hairdresser. Finally, the public sector includes a village health clinic, a school, a mosque, and a cultural center, which require village electricity for outdoor and indoor lighting, refrigeration and television; and a pump for the public well.

These electrical requirements are supplied by the PV systems as shown in figure 4. The system load varies from season to season as identified in table II.

The village power system has a capacity of 28.6 kW_p (peak kilowatts) supplied by 840 PV modules. The nominal 120 V dc battery system consists of 168 cells in 3 strings of 56 cells each with a total storage capacity of 3060 amp-hours at a 16-hour discharge rate. Specific details on these components can be found in their respective descriptions that follow in the section SUBSYSTEM AND COMPONENT DESCRIPTIONS.

The other major components include the power control system, the inverter, and the battery control system (fig. 5). The power control system includes the maximum power controllers (MPC-P10), which regulate the charging currents from the array to the battery. The DECC village inverter converts the bus voltage to 220 V ac. Table III shows the electrical energy which the village and farmhouse systems can provide.

There is an electricity supply priority scheme among the three village sectors which establishes essential and nonessential loads. This permits selective load shedding by the battery control system as required to prevent excessive battery discharge. As initially designed, the residential sector is shed first at 50-percent battery state-of-charge (SOC), the commercial sector second at 40-percent SOC, and the public sector last at 30-percent SOC. However, the priority load shed scheme allows for other settings as desired.

Farmhouse Power System

The farmhouse system includes one remote residence and is a smaller version of the village system, with a capability for lights, refrigeration (if desired), and television. This system load also varies with the seasons as shown in table IV. The farmhouse electric power requirements are supplied by a PV array containing 42 PV modules in three strings of 14 modules each and capable of producing 1.4 kW_p, and a battery containing 56 cells producing a nominal 120 V dc with a capacity of 250 amp-hours at a 16-hour discharge rate. A 1-kW inverter (Abacus) converts the dc bus voltage to 220 V ac to meet the farmhouse needs. The system has one priority level and is diagramed in figure 6.

Water Pumping Systems

The two batteryless water pumping systems are located at an orchard near the remote farmhouse PV power system and at a greenhouse located on a separate farm. These systems are used in conjunction with the drip irrigation method for greenhouse vegetables and fruit trees.

The two systems are powered by batteryless 42-module PV arrays with peak power capacities of 1.4 kW each. A dc pump motor runs at a variable speed as a function of the insolation and the dynamic head. The motor is directly coupled to the vertical turbine pump as shown schematically in figure 7. The output from each system has been estimated at approximately 750 m³/month depending upon the season of the year and the water depth, which varies from 6 to 18 m.

SUBSYSTEM AND COMPONENT DESCRIPTIONS

This section includes descriptions of the basic subsystems with their respective components. So that the village power system can be fully understood, it has been divided into four subsystems: (1) the array subsystem, (2) the control subsystem, (3) the battery subsystem, and (4) the ac output subsystem. The interconnections of these village subsystems and their components are shown in figure 8. Refer to this diagram throughout this section to identify

the specific component under description. Where the farmhouse system has similar components with different specifications, these components are described along with the comparable village units.

Photovoltaic Array

The photovoltaic (PV) array consists of sets of PV modules wired both in series and in parallel to provide the required voltage and current. Utilizing energy from the sun, the cells in the modules produce electricity to power the village and other systems in Hammam Biadha Sud. For the village and isolated farmhouse systems, the electrical energy is also used to charge the batteries. In the water pumping systems for the greenhouse and orchard, the electrical energy supplies only the dc motor.

The PV arrays face south at an adjustable tilt angle designed to capture the most direct sun. The summer optimum angle is 20°, and the winter optimum angle is 50° measured from the horizontal. This adjustment provides an annual average of 4.56 kWh/m²/day or 4 percent more than a fixed array at the approximate latitude of Hammam Biadha Sud.

PV Module

The PV modules have a hard glass cover designed to protect the cells from hail, rain, snow, and blowing sand (fig. 9). The module consists of a sandwich of the glass superstrate, cells, interconnects, terminals, junction box, encapsulant, and back sheet. The protective glass sheet and encapsulated cells are held in a support frame by a one-piece silicone gasket which isolates the assembly from possible shocks transmitted through the frame. Each module produces 35.1 W_p under standard conditions of temperature and insolation.

The Solar Power Corp. SPC G-361 PV module meets the requirements of the Department of Energy (DOE) Specification 5260-2 as modified by the U.S. Air Force Aero Propulsion Laboratory Specification Sheet 79-01 dated November 1, 1979. Specifically, the module tested (1) exceeds temperature requirements of -40 to 50 °C, (2) meets thermal cycling and shock requirements between -40 and 90 °C, and (3) exceeds the 2.5-cm hail requirement.

In addition, measures have been taken to assure protection of the electrical components from shock, humidity, temperature fluctuations, and ultraviolet radiation. The PV modules should require little or no maintenance.

The cell interconnects are made of tinned copper foil with stress relief loops permitting a safety margin for fatigue loading due to thermal stresses. Redundant interconnects enhance the survivability of the module in the event of interconnection loss. The electrical termination is accomplished by a neoprene-jacketed cable with an environmental type connector.

The individual modules are designed with 36 cells in series and 2 bypass diodes, 1 across each group of 18 cells. Bypass diodes serve to permit current to flow through the array when one or more groups of cells has failed. These two bypass diodes can mitigate potential hot spot occurrences. The diodes are

sealed with the environmental connectors in the junction box (J-box) placed at the rear of the modules. All wiring and components in the module J-box are protected from the environment by using a Homoseal coating.

Panel Assembly

The modules were preassembled into panels in the U.S., seven modules in a panel, by using galvanized steel structural elements. The panels are supported on an elevated structure of galvanized steel pipes. The panel structure is designed to withstand heavy dead loads or snow loads, as well as wind loads up to 280 kph.

Array Wiring

The PV panel layouts are shown in figure 10. The design objectives of the wiring scheme are as follows:

- (1) Parasitic and dc wiring losses should be less than 2 percent.
- (2) Voltage and current levels should be compatible with the maximum power controller (MPC) input requirements.
- (3) Installations should be free from electrical hazards to operating personnel.

All module cables are terminated in environmental connectors. If work must be done within a string or group of modules, an array section can be disconnected at the array switchbox. Individual modules may then be disconnected from the wiring harness as required.

As shown in figure 10, the array is divided into four rows. Each row consists of 15 strings. The array wiring is accomplished as follows:

- (1) Each module terminates with a 30-cm pigtail equipped with a plug-in connector.
- (2) Fourteen modules (two panels) called a string are wired in series by plugging them into the supplied wiring harness.
- (3) The harnesses are attached to the row wiring by using wire nuts encased in an epoxy resin.
- (4) The row wiring is terminated in the row junction box. There are 4 row J-boxes, one per 15 strings.
- (5) From the row J-boxes, the wires are run to the array switchbox in the control/battery house via an underground conduit.

Maximum Power Controllers

In order to match the output from the solar array to the charging requirements of the battery for the village and the farmhouse, a power control system

is required. Similarly, to power the water pumping motor systems, a control system is needed. The main component of the power control system is the maximum power controller (MPC).

The MPC is a high-efficiency switching dc-to-dc voltage converter. It converts the PV array voltage from approximately 210 V dc to battery charge voltage (112 to 150 V dc). This is a performance-optimizing procedure increasing the efficiency and reliability of the system, especially in the critical winter months.

The dc-to-dc converters are controlled from a control board. The control board causes the converters to work at one dc voltage ratio, notes the output power, changes the conversion ratio slightly, and notes the power again. The control board then modifies its signal to move the converters into the maximum power range of the array. Once the converters reach the maximum power point, the control unit will hold it constant, varying only slightly from one side of the maximum power point to the other.

The controller also includes special circuitry for smooth, slow startup and for redundant protection against overcurrent or overvoltage at the MPC charger interface at the battery, figure 8.

Each of the four systems employs maximum power controllers:

(1) The village design includes 6 MPC-P10 MPC's (figs. 11(a) and (b)) in a parallel configuration, each controlling 10 strings. These MPC's are slave units, acting independently, but under the control of the master battery control and display box (fig. 12).

(2) The farmhouse design has 1 MPCB-P4 MPC (fig. 13) for the 42 PV modules in that array.

(3) The water pumping systems for the greenhouse and the orchard each have 1 MPC-P3 MPC for the 42 PV modules in each of the arrays.

The maximum power controllers for the village and the farmhouse serve to match the output voltage of the solar array (which is a function of its output current, temperature, and insolation) to the charging voltage of the battery (which is a function of its state-of-charge, charging current available, temperature, and past charging history). This solid-state power and control unit in the village and farmhouse systems has the ability to match the array and battery voltages by performing several key functions:

(1) It changes the varying solar array dc nominal voltage of 210 V to the dc battery level of 112 V with 90 to 98 percent efficiency.

(2) It utilizes the maximum power output of the solar array in order to improve system performance.

(3) It eliminates the need for a separate series isolation diode on each group of modules, thus reducing electrical loss.

(4) It responds to the battery state-of-charge (SOC) estimator for battery charge control functions.

(5) It responds to manual control for disconnecting the solar array from the battery.

The MPC's solid-state circuitry provides for long life, and its modular design facilitates rapid fault diagnosis and repair.

In the water pumping systems, the MPC couples the array to the motor/pump assembly by downconverting the voltage of the array output to the operating voltage of the dc motor. The motor voltage selected by the MPC is that which optimizes the operational speed of the motor (motor speed is proportional to motor voltage) for a given level of solar intensity. The MPC also automatically starts the system at sunrise and shuts it down at sunset, simplifying operation of the pumping.

Battery Storage Subsystem

The function of the battery in a photovoltaic system is to store electric energy produced by the solar array for use when there is low or no solar energy. For photovoltaic systems, batteries must meet requirements for long periods for operation, minimum maintenance, and harsh environments. In addition, the recharge efficiency must be high, and self-discharge must be low. Finally, the ability of the battery to function reliably after extended periods of partial discharge is necessary.

The battery chosen for this project has lead calcium grids which provide minimal water loss, high-charging efficiency, and negligible self-discharge. This battery also has excess electrolyte, which gives an increased capacity, lower freezing point, and reduced maintenance requirements. The selected C & D type QP battery is also designed for deep daily discharge service. The village system utilizes 168 QP75-25 cells in three strings of 56 cells each. The battery storage capacity is rated at 360 kWh at 120 V dc with a capacity of 250 amp-hours at the 16-hour discharge rate. In this system, the cells are arranged with six to a tray.

The groups of cells in each system are assembled by using Anderson-type quick-disconnect power connectors to facilitate battery replacement if required. The batteries are connected to the battery control and display box through the battery switchbox.

Battery Control Subsystem

Battery charging requires proper charge control and monitoring to prevent damage to the battery and to maximize battery life, while maintaining system efficiency. The battery control subsystem includes a state-of-charge (SOC) controller which also continually displays the battery state-of-charge as a percentage on an LCD meter. This monitoring of the SOC improves the overall battery system performance as it

- (1) Increases battery life by decreasing electrical stress during charging
- (2) Provides more useable battery capacity under varying demand and temperature conditions

- (3) Increases system efficiency with better use of available solar input
- (4) Provides accurate monitoring of available battery energy

The major components of the village battery control subsystem are the battery display and control box (fig. 12), which includes the SOC meter, and the separate battery switchbox. The two boxes have the capability of continuously monitoring and analyzing the available energy from the battery storage.

The SOC of a battery is a function of the battery's voltage, charging current, and temperature, and the battery's past history. The SOC controller measures these parameters and then computes the present SOC and the optimum amount of equalization charge for those particular conditions. The controller performs the following functions:

- (1) Integrates current flow in and out of the battery to determine the battery SOC
- (2) Activates status lights to indicate full charge, low-battery warning, and low-battery shutdown
- (3) Activates shutdown signal when battery state-of-charge (SOC) reaches preset level
- (4) Controls overcharge at the end of charging cycle
- (5) Monitors battery temperature and voltage to prevent excessive battery discharge or overcharge

The control unit works together with the charge monitoring unit. The charge monitor records the net charge into and out of the battery while accumulating the ideal amount of equalization charge the battery will need at the end of that charge cycle. When energy is available, this amount of equalization charge is given to the battery to recondition it and prolong its life.

The information supplied by the charge monitor is acted upon by the control unit. Once the battery discharge has reached a predetermined point, the control circuit will signal the ac load control box (fig. 14) to shed a load sector. This prevents excessive battery discharge. At the other extreme, the control will shut down the MPC's when the battery is fully charged and sufficient extra charge has been introduced into the battery and gassing has begun. Gassing stirs the electrolyte battery and ensures full charging of the battery plates. The control unit and the MPC's operate in their normal maximum power delivery mode when the battery charge lies between a full charge level and a preset load-cutoff charge level.

The SOC unit protects the battery and insures a long, low-maintenance battery life. Also, it guards against undercharging, overcharging, fouling of the battery plates, and stratification of the battery electrolyte. Overcharging and undercharging, which make maintenance procedures more demanding and more frequent, are the two main threats to the life of the battery.

In the farmhouse system, the SOC controller is combined with the maximum power controller into one unit as shown earlier in figure 13.

Power Conditioning Units

A power conditioning unit (PCU) is basically an inverter/transformer combination which changes the dc electricity generated by the solar array and available from the battery into appropriate ac power. The village system inverter (DECC No. 61313) was selected to match the village requirements with maximum reliability and minimum maintenance. This inverter, rated at 15 kVA, has a nominal input voltage of 112 V dc and a 220-V ac, 50-Hz single-phase output. The farmhouse inverter is rated at 2 kVA and also has a nominal input voltage of 112 V dc and a 220-V ac, 50-Hz single-phase output.

The village PCU (fig. 15) is cooled by two blowers. A thermal detector is installed inside the equipment cabinet. If insufficient cooling is provided because of the failure of a blower, or, if the temperature exceeds a set value, the overtemperature protection circuitry prevents damage to the unit by shutting it off. The unit restarts automatically when the temperature drops below 54.4 °C.

The input power to the PCU is controlled by circuit breakers located on the battery box front panel. The soft-start circuitry limits the inrush current at turn-on by temporarily electrically inserting resistors into the input line. The resistors are bypassed after approximately 1 sec to avoid unnecessary power dissipation.

The PCU logic monitors the inverter output. If an overload condition is sensed, the output is current limited. If the overload condition persists for more than 10 sec, the logic gates off all the inverters and generates an error indication at the front panel. The PCU provides current limiting at 110 percent of the rated load current. It can, however, provide 150 percent of the rated load current on a transient basis (0.05 sec). If the PCU current limits for a period of more than 10 sec, overcurrent disconnect circuitry will turn the unit off and the OVERCURRENT lamp on the front panel will be illuminated. The overcurrent disconnect must be reset manually. When an output undervoltage condition is sensed, the OVERCURRENT lamp is illuminated, and the unit shuts down and must be reset manually by means of the RESET switch.

Alternating Current Load Control Box for Village System

The ac load control box (fig. 14) implements the shedding of loads. Control signals to initiate load shedding by the ac load control box are provided from the battery control and display box. The ac load control box is electrically located between the inverter and the ac loads. The ac loads are divided into three sectors, each of which can be individually disconnected as shown in figure 16.

The block diagram shows the splitting of loads by sector and priority so that selective load shedding by the ac load control box can be implemented automatically. The shedding scheme includes dropping first the priority 3 loads, then the priority 2 loads, then the priority 1 loads. Finally, the PCU is turned off, and all contactors drop out to avoid further battery discharge. Since the state-of-charge signal is derived from an integrated charge, it is noise free and can be very accurately monitored to achieve this distribution control strategy.

Load sectors can be disconnected in two ways: (1) manually by using the appropriate disconnect switch located on the front panel or (2) automatically by means of the battery control and display box commanding the ac load control box to sequentially shed load sectors as the battery state-of-charge falls below adjustable threshold values. The sectors are automatically reconnected when the battery state-of-charge reads 10 percent over the threshold value. This hysteresis prevents excessive cycling. The load disconnect/reconnect sequence was initially designed for the following settings:

| Priority | Sector | State-of-charge when disconnected, percent | State-of-charge when reconnected, percent |
|----------|-------------|---|--|
| 3 | Residential | 50 | 60 |
| 2 | Commercial | 40 | 50 |
| 1 | Public | 30 | 40 |

Each load sector is individually monitored by using kilowatt-hour meters. Load sector currents can also be monitored by using separate current meters.

Monitoring Equipment

The philosophy of the monitoring subsystem design is to provide sufficient data for determining two types of information: (1) instantaneous quantities to ensure that the system is working properly and (2) cumulative quantities to record the amount of energy delivered over a long period to measure system overall performance

The following sections present a summary of the monitoring instrumentation.

Village power system. - The instrumentation provided with the village power system provides for dc/ac measurements as shown in table V.

The village control unit has built-in test equipment which permits rapid system malfunction diagnosis. Simply by the turn of a selector switch, the user can check battery state-of-charge, array string voltages, MPC output current, battery voltage, battery current, and a self-testing measure.

The village battery display and control box calculates battery state-of-charge and displays the following system parameters:

- (1) Battery state-of-charge as a percentage of battery capacity from 30 to 100 percent (for state-of-charge below 30 percent, a LO BATT indication appears in the display)
- (2) Low-charge warning (for battery states-of-charge between 30 and 50 percent, a yellow light is illuminated; for states-of-charge below 30 percent, a red light is illuminated)
- (3) Battery output bus voltage
- (4) PV array current

- (5) Battery current (a + symbol appears when the battery is receiving a net charge)

Each of the six maximum power controllers (MPC's) can be manually turned on or off from the front of the battery display and control box. Manual ON provides for maximum charging up to the fixed 150-V MPC limit. Manual OFF turns off the MPC regardless of battery status. There is also an AUTO position on the MPC switches. When switched to this position, the MPC provides automatic battery equalization and charge termination in response to the state-of-charge calculated by the battery display and control box.

Farmhouse power system. - The farmhouse power system instrumentation provides for the measurements shown in table VI.

The farmhouse power system has a combined MPC and SOC controller as shown in figure 13. It displays the following:

- (1) Battery state-of-charge as a fraction of full charge (a plus sign will appear to the left of the number 1.00 when the MPC is in its equalization mode, reconditioning the battery)
- (2) A red battery-charge warning light, which is illuminated when the battery charge is low enough to necessitate disconnecting all loads
- (3) A yellow battery-charge warning light, which is illuminated when the battery charge approaches the load disconnect value and when energy should be conserved

The combined MPC and SOC controller also has a load control switch which disconnects the load bus when in the OFF position. When in the ON position, the load bus is controlled by the state-of-charge unit. The switch is located on the front panel. The controller utilizes a thermistor to sense battery temperature for overcharge regulation.

Water pumping systems. - The two PV-powered water pumping systems are located at the farmhouse orchard and at a remote greenhouse. The pump near the farmhouse is used for the irrigation of a hectare of fruit trees. The greenhouse pump is used for vegetable irrigation. Both systems are identical, with electricity going directly to the dc motor with no battery storage and no inverter.

In the case of the greenhouse pump system, the design is based upon the need for irrigation as well as for water storage. In the case of the fruit trees pump system, the design is based upon the average daily need of the trees.

The array for each system is composed of 42 modules having a total capacity of 1.43 kW_p. The required flow rate is 132 liter/min at a head of approximately 24.4 m. The PV system is designed to produce the maximum amount of water based on nominal average insolation.

The pumping system is composed of the PV array coupled to a motor/pump assembly through a power control system which includes a maximum power controller. The electronic circuits in the power control system track the maximum power point of the array and optimize the power going to the motor.

The permanent magnet high-efficiency direct current pump motor is specially adapted to match the pump system. For this type of system, the motor is operated at a variable speed according to the amount of sunlight available. The motor is mounted vertically on top of the pump (fig. 17), and the motor shaft is coupled to the pump shaft.

The pump is a 26-stage vertical turbine pump with a steel shaft, bronze impellers, and a cast iron discharge head. It is manufactured by Peabody Floway. Water enters the pump, is pushed upward by the rotating action of the impellers, and exits above ground level through the discharge head to be piped to site location for use.

When the OFF/ON switch is in the ON position, the system is regulated automatically. The array is coupled to the motor/pump assembly by downconverting the voltage of the array output to the operating voltage of the dc motor. The system starts up automatically shortly after sunrise (at about 20 to 25 percent of full (noontime) sunlight) and shuts down shortly before sunset (again at about 20 to 25 percent of full (noontime) sunlight).

Both irrigation systems contain cumulative flowmeters to measure water delivered by the system.

INSTALLATION AND OPERATION

All site preparation and local construction, including the battery storage and electrical control building, the PV array foundations and understructure, and the distribution grid, were completed by STEG or STEG contractors prior to the installation of the U.S.-procured hardware. Also, the two wind-powered water pumpers, which were designed and manufactured in Tunisia, the three special greenhouses with thermal storage walls, and the solar hot water system for the village clinic were completed before the PV systems were installed. Like the wind-powered water pumpers, the greenhouses and solar hot water systems were constructed by using local materials and host-country skills.

Installation of the PV systems took place during January and February 1983. Four separate and independent systems were installed by a team composed of Solar Power Corp., NASA, and STEG personnel. Local assistance was also provided by the villagers in many aspects of the installation. The village 27-kW_p power system was installed at the east end of the village adjacent to the main road (figs. 18 and 19). The 1.4-kW_p system for a farmhouse was installed on a farm located just south of the village, but too distant to be connected to the village grid (fig. 20). A separate 1.4-kW_p system was installed on the same farm to pump water for a drip irrigation system used for a new orchard of young fruit trees (fig. 21). The fourth PV system was installed on a farm northwest of the village to pump water for irrigation of greenhouse crops (fig. 22). The four systems were designed to have the maximum amount of commonality in order to reduce the critical spare parts inventory required and to simplify the operation and maintenance procedures.

All four systems were in an initial operational status by February 5, 1983. Electrical power from the PV system was supplied to the village distribution grid so that the system could be checked out and on-site acceptance tests could be performed. The initial village loads consisted of fluorescent lights in each of the residences, in the school, and in the other public and

commercial sector buildings, together with a few TV's and radios, and the medical refrigerator in the clinic. During the checkout operation by the contractor, both the village and farmhouse inverters shut down automatically and could not be reactivated under normal load conditions. The cause of the village inverter shutdown was a high-input voltage condition that occurred inadvertently during the checkout operation. This resulted in damage to integrated circuits contained in the inverter logic module. The contractor was subsequently able to obtain the necessary parts from a Tunisian electronics supply store and repair the unit in the field. The farmhouse inverter problem was not correctable in the field, and the entire chassis was replaced by the U.S. supplier. The water pumping systems experienced no startup problems.

Following correction of the inverter problems and other minor problems normally associated with new system startups, the four PV systems passed acceptance tests on March 19, 1983. During the startup and acceptance phase, Tunisian technicians and engineers were trained in the operation, maintenance, and troubleshooting procedures for the systems. Project support was also provided by the U.S. Peace Corps. The Peace Corps provided two volunteers who lived in the village for 2 years and assisted in the introduction of new agricultural methods (e.g., greenhouse farming and drip irrigation). They also assisted in teaching energy conservation in conjunction with the limited energy aspects of the solar energy systems.

During the first 3 months of operation after final acceptance, some electrical problems were encountered with the controls and power conditioning of the ac systems. Primarily, these problems were concentrated in the maximum power controllers, the battery state-of-charge regulator, and the PC unit. Since June 1983, the village power system has operated continuously without an unintended interruption of service. Aside from a direct lightning strike on one of the PV-powered water pumping systems, the water systems have worked trouble free. There have been, however, additional problems with the farmhouse inverter, some of which may have been caused by wiring problems in the farmhouse.

In accordance with the project plan, systems operation is performed by the Tunisians in order for them to become familiar with and gain experience from the solar technologies being demonstrated. Their responsibility includes recording, reducing, and analyzing the technical performance data. In addition to the instrumentation provided to monitor the PV systems performance, a small meteorological station was installed in the village PV array field to monitor solar insolation, air temperature, wind speed and direction, and barometric pressure. STEG has been monitoring system performance as part of the ongoing project evaluation process. When the project was initiated, a 2-year demonstration phase was planned by STEG and U.S. AID during which time the solar technologies would be evaluated from social, economic, and technical viewpoints. The reader is referred to STEG for any information regarding the technical as well as social aspects of the solar energy applications.

COST CONSIDERATIONS

Cost effectiveness, per se, was not a primary factor in implementing the solar technology demonstrations at Hammam Biadha Sud. No cost analyses were conducted to compare types of solar technologies or combinations of technologies in order to select the most economical approach for supplying electric

power to the villagers. For example, whether extension of the national grid would be more economical than a stand-alone solar energy system was not at issue. The decision to demonstrate solar energy technologies for rural, agricultural applications had already been established in the project paper and the project grant agreement (AID Project No. 664-0325) when NASA was requested to manage the project implementation phase with STEG. Specifications and requirements evolved from the conceptual stage to the final design stage. The guidelines given NASA were to procure the largest system (within budgetary constraints) that (1) allowed for as many as possible of the villagers to benefit from the service (i.e., assume 100-percent participation initially), (2) included some allowance for population growth (e.g., 10 percent per year for the first 3 years), (3) provided the same electrical characteristics as the national grid (i.e., 220 V, 50 Hz, single phase), and (4) stressed system reliability and component repairability in the field. The reason for the last requirement was to ensure maximum system availability, since the demonstrations were aimed at providing the Tunisians with direct experience and hardware familiarization in the event the solar technologies became cost effective and were found suitable to meet specific future needs of the country.

An attempt has been made, however, to determine the cost per peak watt for a replication of the village PV power system. The replication costs exclude all cost elements of a first-of-a-kind nature, experimental cost elements (e.g., extra instrumentation), project management, and training costs. Some development costs could not be accurately defined because of the way cost information was reported by the contractor. Also excluded were the site preparation and services-in-kind contributions of the host country.

The PV module costs were \$11.00 per peak watt free on board (FOB) from the factory. The balance of systems (BOS) costs were approximately \$15 per peak watt, based on the above exclusions. The total system cost of \$26 per peak watt for the Hammam Biadha PV system is compared with other PV applications in table VII, which is reproduced from reference 2.

The estimated annual energy consumption at Hammam Biadha is approximately 20 000 kWh. According to reference 3, the cost break-even point for a PV system costing \$20 per peak watt (1982 dollars) occurs at 6000 kWh or less when compared with a small 4-kVA diesel generator. For an annual energy consumption of 20 000 kWh, the PV energy cost would have to be less than \$1.00 per kWh to compete with diesel-generated power. In comparison, by considering only the capital cost and by assuming a 20-yr lifetime, the PV-generated electricity costs over \$2.00 per kWh for a replicated Hammam Biadha system. For additional information on PV, diesel, and hybrid PV-diesel system comparisons, the reader is referred to reference 4.

CONCLUDING REMARKS

Several solar energy systems including passive thermal energy, wind, solar hot water, and photovoltaics were installed at the village of Hammam Biadha Sud. The systems, which are part of a demonstration of renewable energy applications to meet the needs of a rural agricultural community, have been in operation for more than 40 months.

Initial reaction to the solar energy applications has been positive. However, these demonstrations represent only a small step in determining the

merits of using alternative energy resources in assisting the development and in improving the quality of life in rural Tunisia. A more thorough evaluation of the specific applications at Hammam Biadha will require a followup study of the economic and social impact of the solar electric system on the village as well as a study of the value and applicability of the drip irrigation and greenhouse farming techniques to the local farm region. Of particular interest is whether the villagers will continue to be satisfied with an energy-limited power source as their annual energy consumption approaches the system limit.

As the Tunisian engineers and technicians become expert in the application of the technologies through system operation, the system reliability and long-term maintenance requirements will be important factors, along with the sociological and economic considerations, in determining the limitations and values of selected renewable energy technologies. It is hoped that the results of this demonstration project will assist Tunisian planners in the determination of when, where, and if renewable energy systems should be introduced into their rural development programs.

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2. Bifano, W.J., et al.: Status of DOE and AID Stand-Alone Photovoltaic System Field Tests. 17th IEEE Photovoltaic Specialists Conference, IEEE, 1984, pp. 1159-1167.
3. Bifano, W.J.: Economic Viability of Photovoltaic Power for Development Assistance Applications. 16th IEEE Photovoltaic Specialist Conference, IEEE, 1982, pp. 1183-1188.
4. Brainard, W.A.: Analysis of the Economics of Photovoltaic-Diesel-Battery Energy Systems for Remote Applications. American Solar Energy Society, Minneapolis, Minnesota, June 1-3, 1983.

TABLE I. - MAJOR SYSTEM COMPONENT SOURCE AND RESPONSIBILITY

| System/subsystem | Source | Lead responsibility |
|---------------------------------|---------|---------------------|
| Village PV system | U.S. | NASA |
| Farmhouse PV system | U.S. | NASA |
| Water pumping PV system | U.S. | NASA |
| Solar hot water system (clinic) | Tunisia | STEG |
| Solar heating system (deleted) | Tunisia | STEG |
| Wind-powered pumping system | Tunisia | STEG |
| Solar greenhouses | Tunisia | STEG |

TABLE II. - VILLAGE DESIGN LOAD PROFILE

[Numbers in parentheses represent the number of units in each sector.]

| | Kilowatt hours per day | | | |
|---|------------------------|-------------|-------------|-------------|
| | Spring | Summer | Fall | Winter |
| Commercial sector (Two stores, mill, hairdresser) | | | | |
| Lights (11) | 0.74 | 0.60 | 0.74 | 1.18 |
| Refrigerators (2) | <u>3.51</u> | <u>4.66</u> | <u>3.51</u> | <u>2.02</u> |
| Subtotal | 4.25 | 5.26 | 4.25 | 3.20 |
| Domestic sector (22 homes) | | | | |
| Lights (91) | 10.92 | 4.96 | 10.92 | 14.88 |
| Refrigerators (13) | 20.91 | 29.89 | 20.91 | 11.98 |
| Televisions (18) | <u>1.90</u> | <u>1.90</u> | <u>1.90</u> | <u>1.90</u> |
| Subtotal | 33.73 | 36.75 | 33.73 | 28.76 |
| Public sector ^a (Clinic, school, mosque, cultural center, pump) | | | | |
| Lights (57) | 10.76 | 2.22 | 10.76 | 11.56 |
| Refrigerators (3) | 6.68 | 4.61 | 6.68 | 3.86 |
| Medical refrigerator (1) | 0.75 | 0.75 | 0.75 | 0.75 |
| Televisions (3) | 0.24 | 0.10 | 0.24 | 0.24 |
| Pump (1) | <u>1.50</u> | <u>1.09</u> | <u>1.04</u> | <u>1.15</u> |
| Subtotal | 19.93 | 8.77 | 19.47 | 17.56 |
| Total | 57.91 | 50.78 | 57.45 | 49.52 |

^aDoes not include coffee shop, which was added at later date.

TABLE III. - DAILY AVERAGE ac ENERGY OUTPUTS^a

| Month of year | Village system, kWh/day | Farmhouse, kWh/day |
|---------------|-------------------------|--------------------|
| January | 67.4 | 3.4 |
| February | 81.3 | 4.1 |
| March | 89.0 | 4.4 |
| April | 103.4 | 5.1 |
| May | 114.7 | 5.8 |
| June | 116.4 | 5.8 |
| July | 119.0 | 6.0 |
| August | 108.5 | 5.5 |
| September | 101.2 | 5.0 |
| October | 84.1 | 4.2 |
| November | 72.3 | 3.6 |
| December | 64.8 | 3.3 |

^aBased on an average inverter efficiency of 80 percent.

TABLE IV. - FARMHOUSE DESIGN LOAD PROFILE

| Load | Kilowatt hours per day | | | |
|------------------|------------------------|--------|------|--------|
| | Spring | Summer | Fall | Winter |
| Lights (5) | 0.48 | 0.24 | 0.48 | 0.72 |
| Refrigerator (1) | 1.61 | 2.30 | 1.61 | 0.92 |
| Television (1) | 0.11 | 0.11 | 0.11 | 0.11 |
| Total | 2.20 | 2.65 | 2.20 | 1.75 |

TABLE V. - VILLAGE SYSTEM INSTRUMENTATION

| Instrumentation | dc/ac Measurements |
|---------------------------------|--|
| Each of the six MPC's | Array string input voltage by string Array string current by string |
| Battery display and control box | Battery voltage Battery current Array charging current Battery state-of-charge LCD display of the battery state-of-charge |
| Battery switch | Voltage of each of the battery strings Current of each of the battery strings |
| ac Load control box | Output current by village sector Cumulative kWh by village sector Load shedding status indicators |
| Inverter | Inverter output voltage Inverter output current |

TABLE VI. - FARMHOUSE SYSTEM INSTRUMENTATION

| Instrumentation | dc/ac Measurements |
|--------------------------|--|
| Maximum power controller | Array input voltage by string MPC output current by string Battery voltage Battery current Battery state-of-charge |
| PCU (inverter) | ac Voltage ac Current |

TABLE VII. - COST BREAKDOWN FOR PV SYSTEM FIELD TESTS

[From ref. 2.]

| Application | System size, kW (peak) | Cost, \$/W | | |
|-----------------------------------|---------------------------|---------------|-----|-------|
| | | PV modules | BOS | Total |
| Medical systems | 1.4 | 10 | 21 | 31 |
| Remote satellite Earth station | 1.6 | 8 | 22 | 30 |
| Village power | 8.0 | 8 | 24 | 32 |
| Community services | | | | |
| General purposes | 5.4 | 10 | 21 | 31 |
| Water pumping | 6.4 | 10 | 10 | 20 |
| Village power (Hammam Biadha) | 33 | 11 | 15 | 26 |

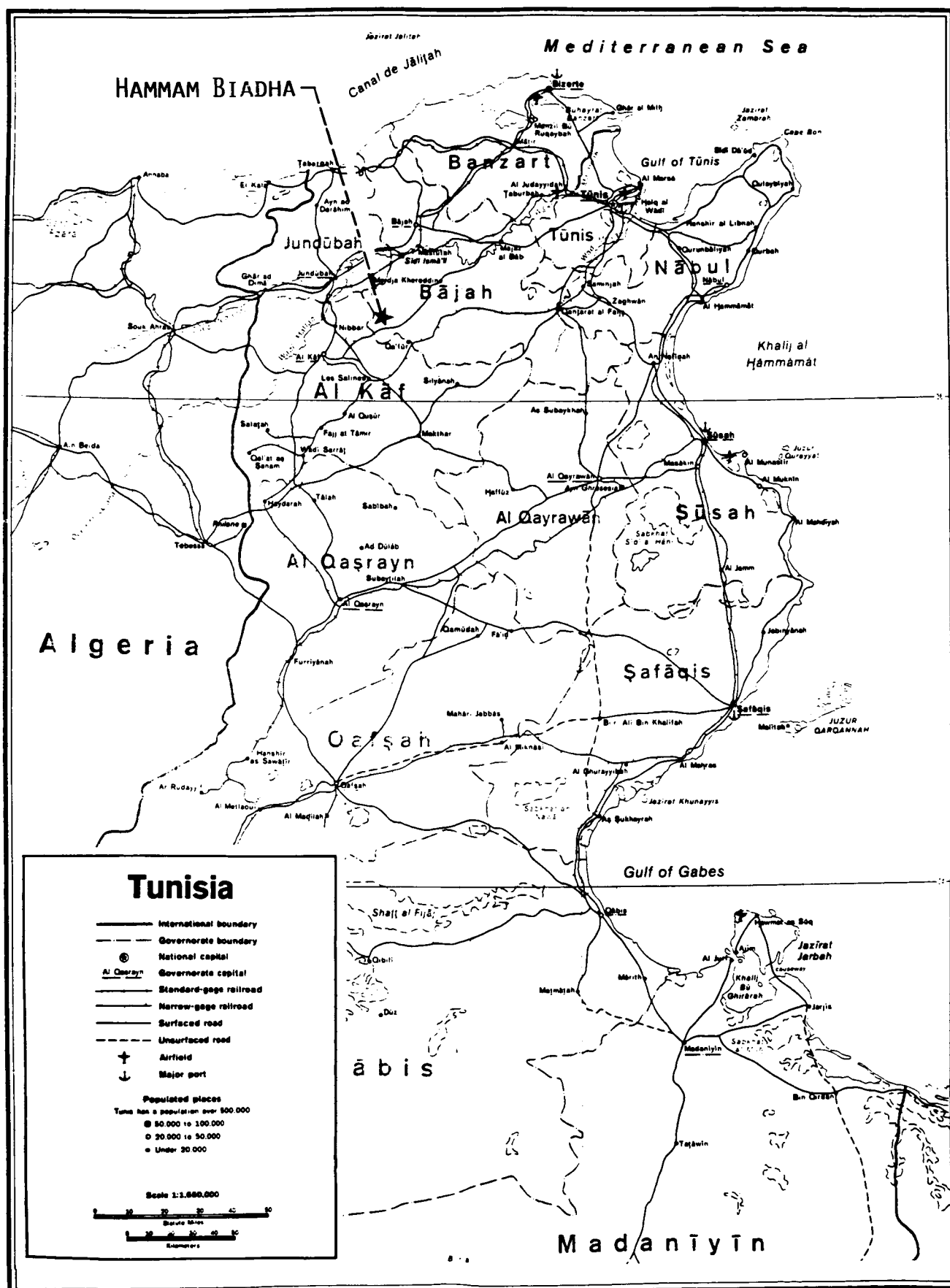


FIGURE 1.- MAP OF TUNISIA SHOWING LOCATION OF HAMMAM BIADHA.

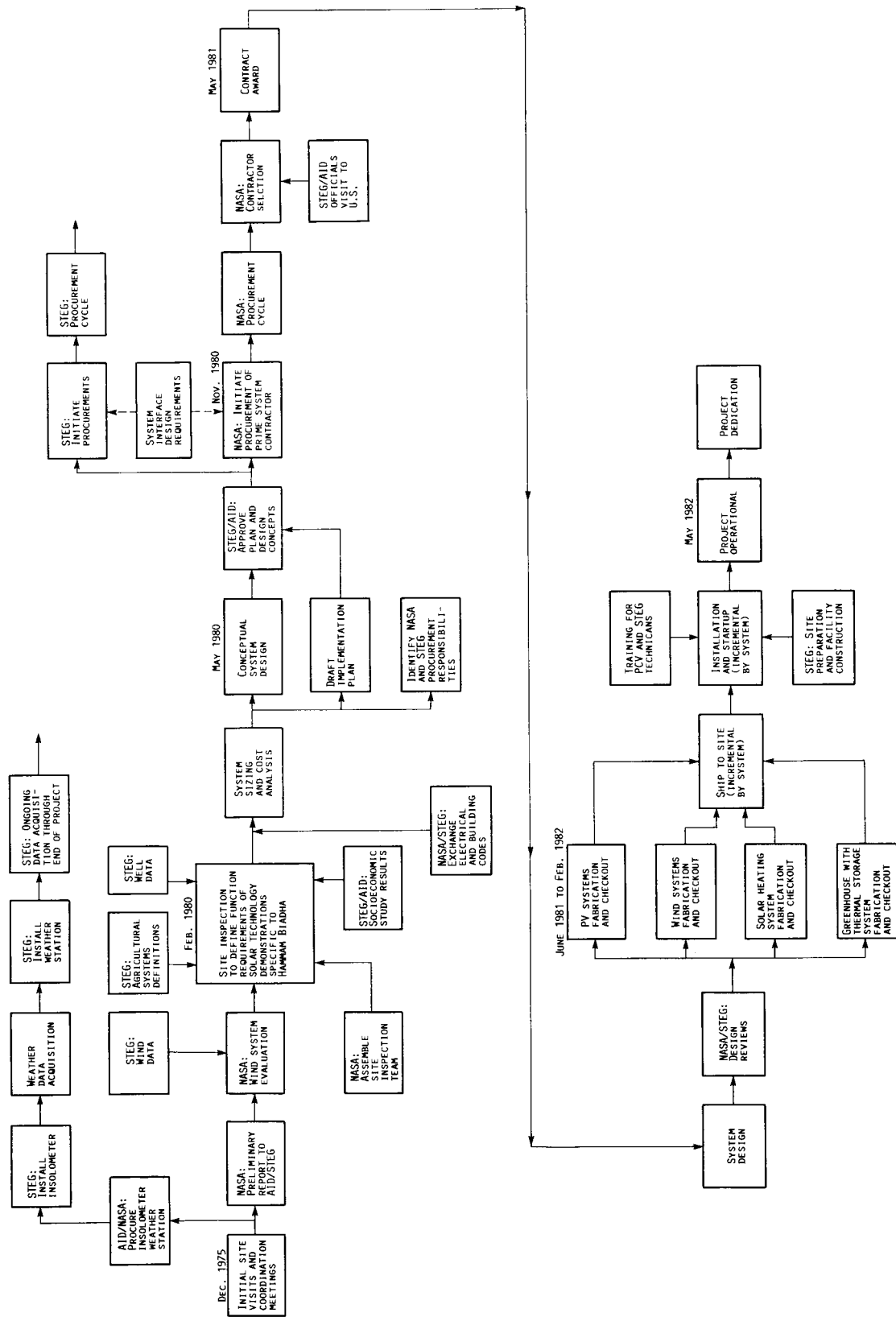


FIGURE 3. - ACTIVITY FLOW DIAGRAM FOR TUNISIA RENEWABLE ENERGY PROJECT, DISTRICT ENERGY SUBPROJECT.

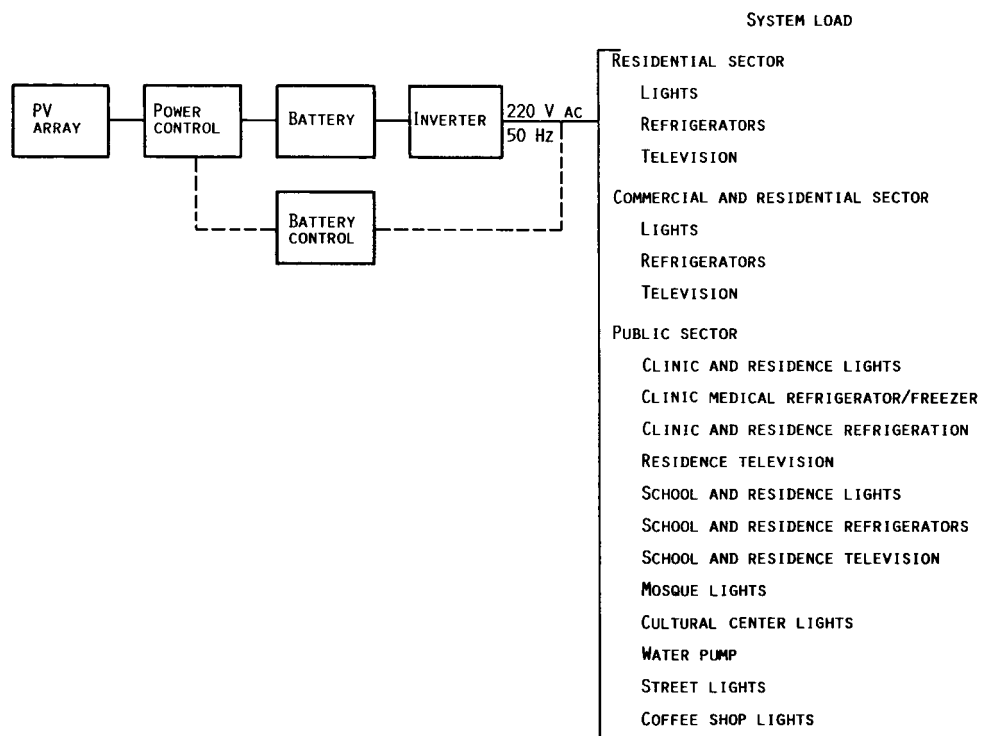


FIGURE 4.- VILLAGE PV SYSTEM LOAD SECTORS.

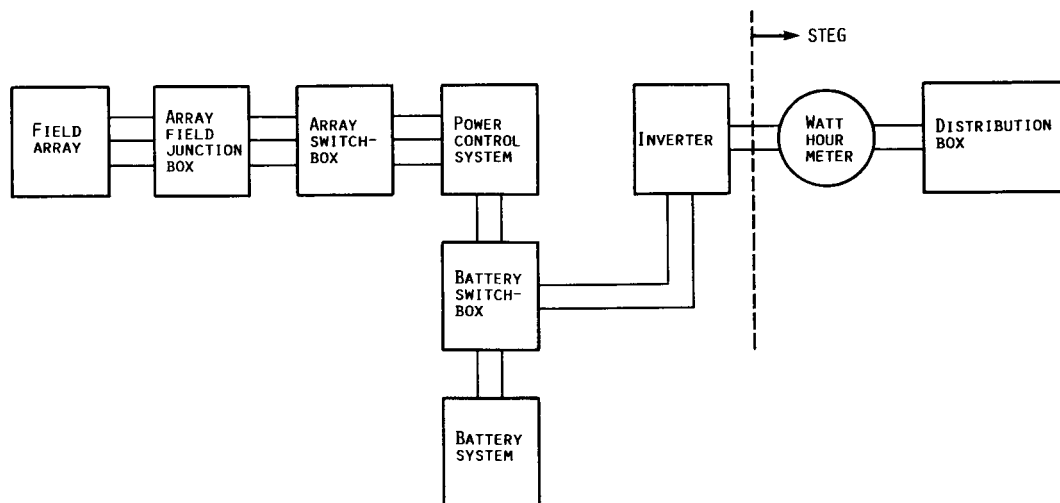


FIGURE 5.- PV SYSTEM COMPONENTS.

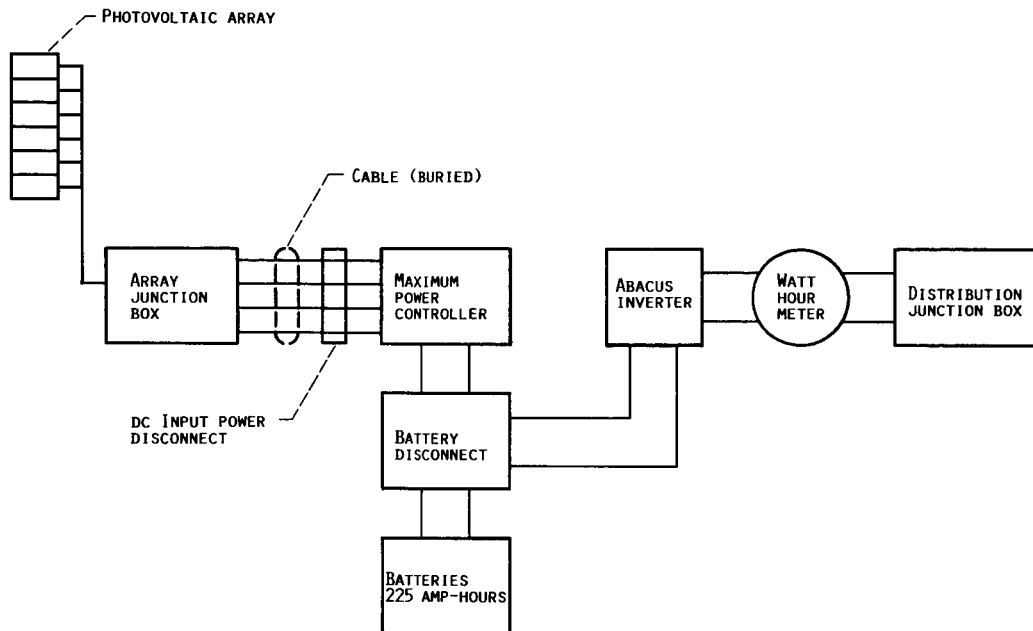


FIGURE 6. - FARMHOUSE SYSTEM COMPONENTS.

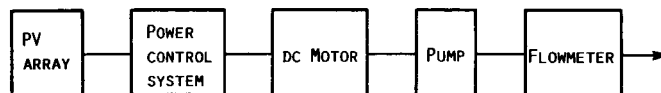


FIGURE 7.- PUMPING SYSTEM COMPONENTS.

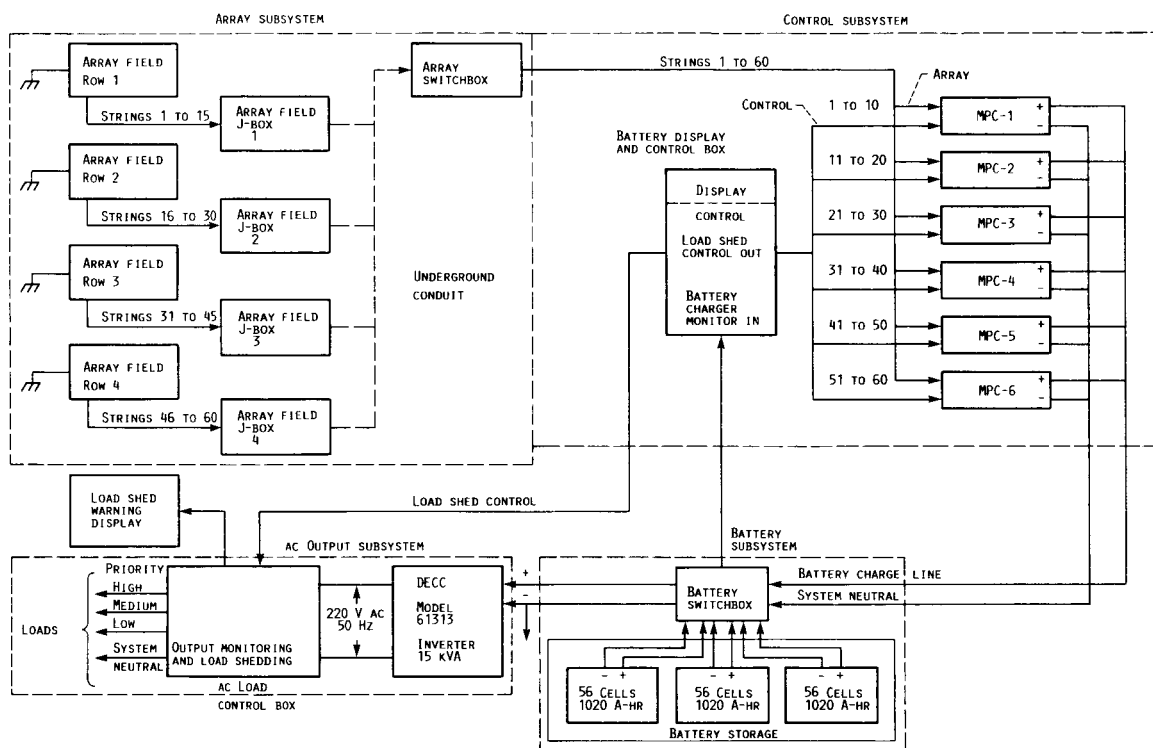


FIGURE 8.- VILLAGE SYSTEM BLOCK DIAGRAM.

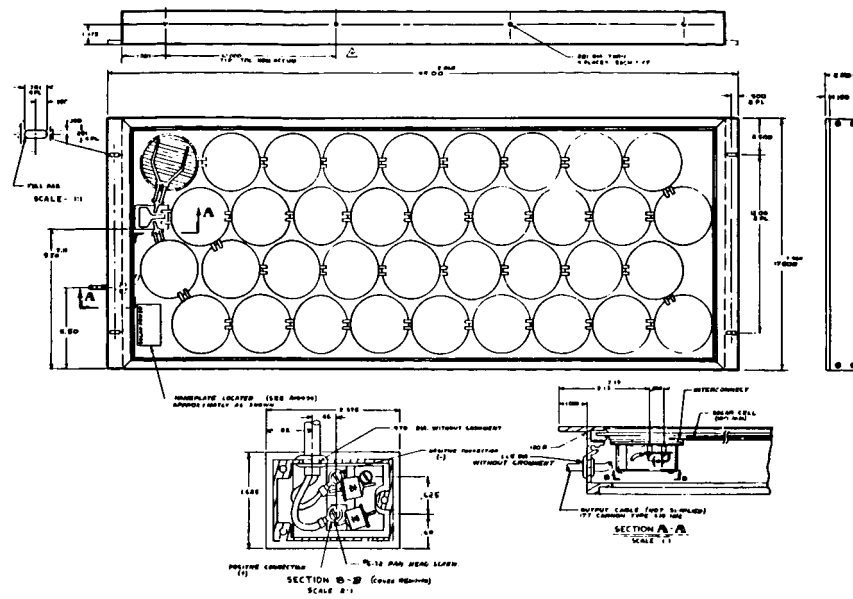


FIGURE 9.- PV MODULE.

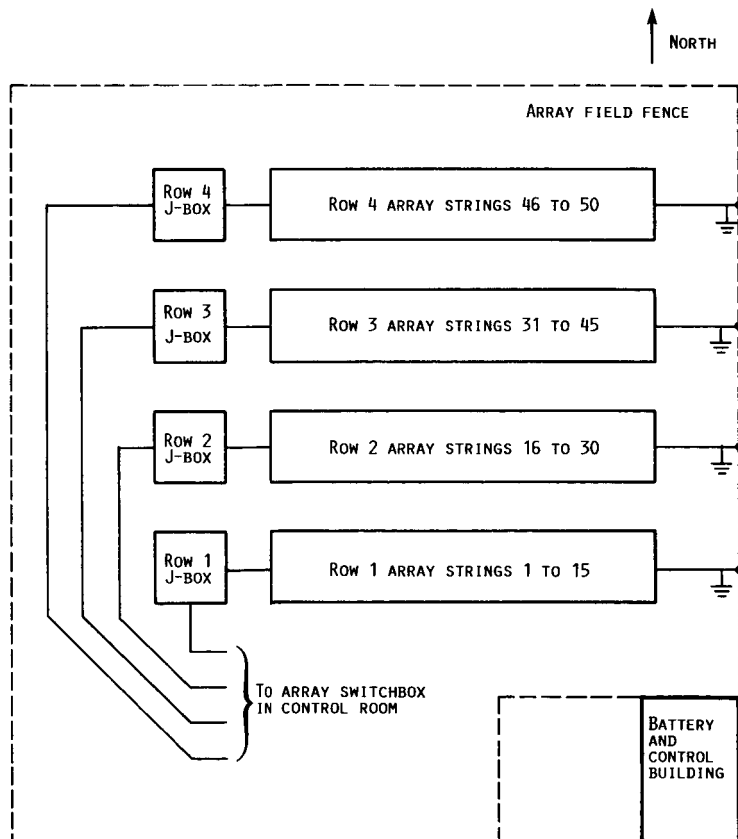
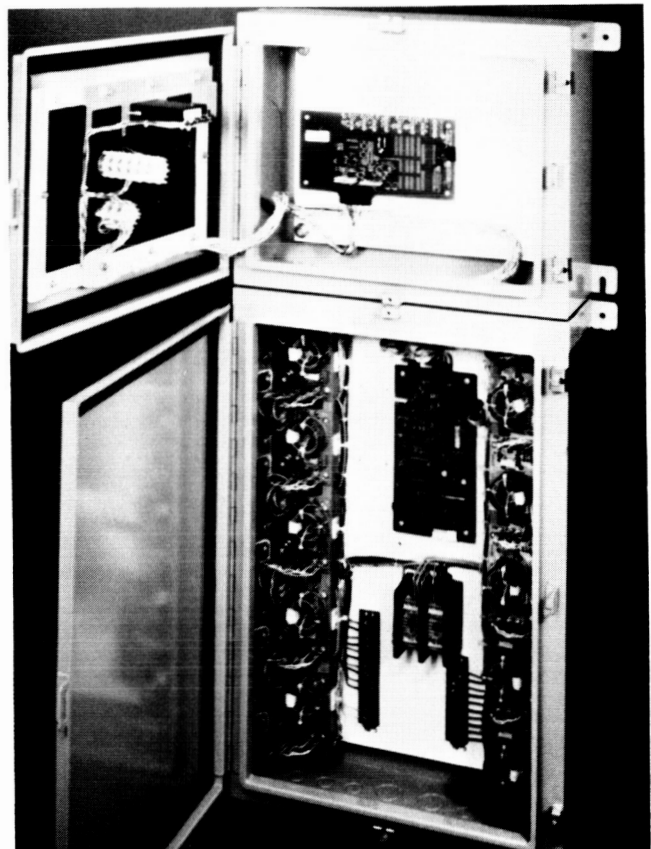


FIGURE 10.- VILLAGE ARRAY FIELD WIRING.

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(A) CLOSED.



(B) OPEN.

FIGURE 11. - VILLAGE MAXIMUM POWER CONTROL UNIT.

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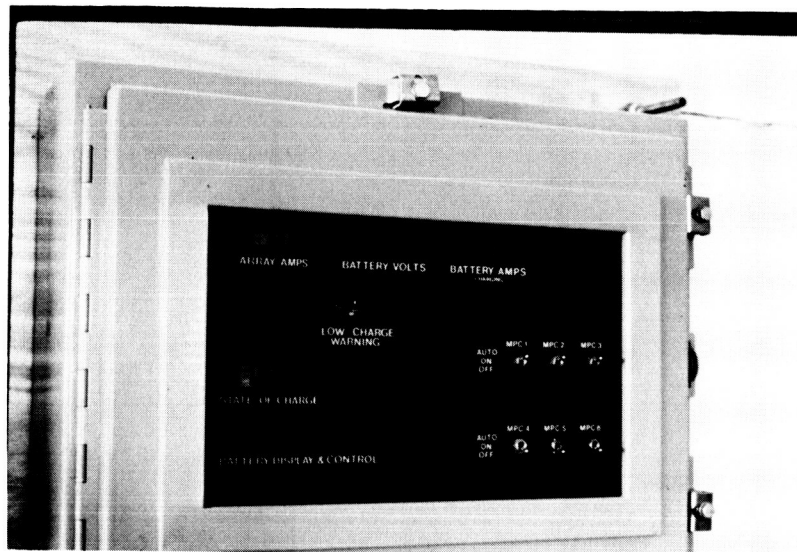


FIGURE 12. - VILLAGE BATTERY DISPLAY AND CONTROL UNIT.

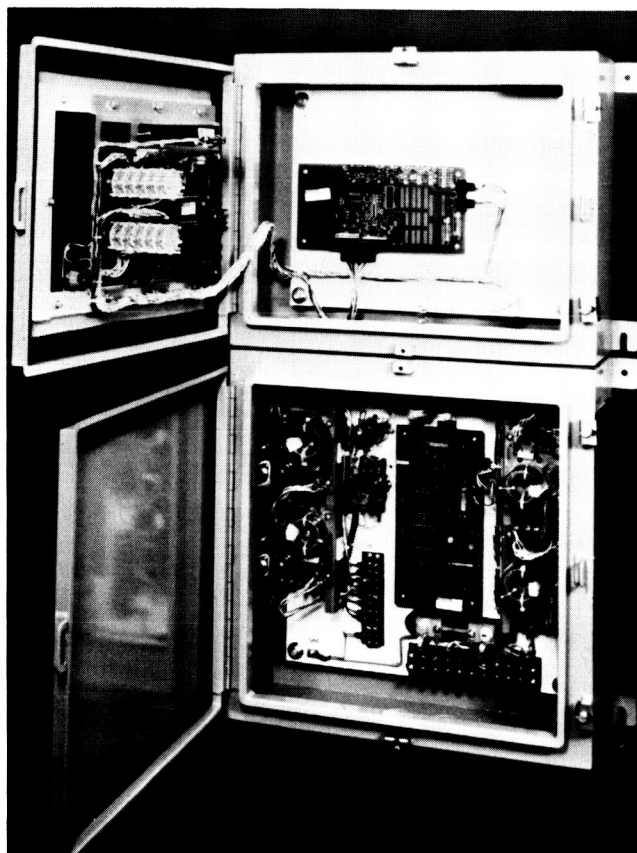


FIGURE 13. - FARMHOUSE MAXIMUM POWER CONTROL UNIT.

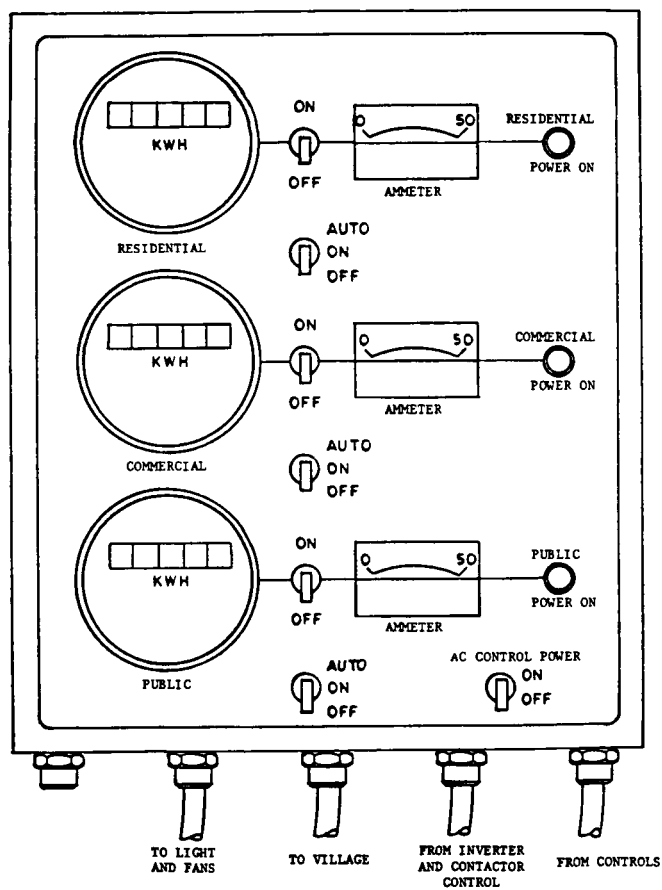


FIGURE 14.- ALTERNATING CURRENT LOAD CONTROL BOX.

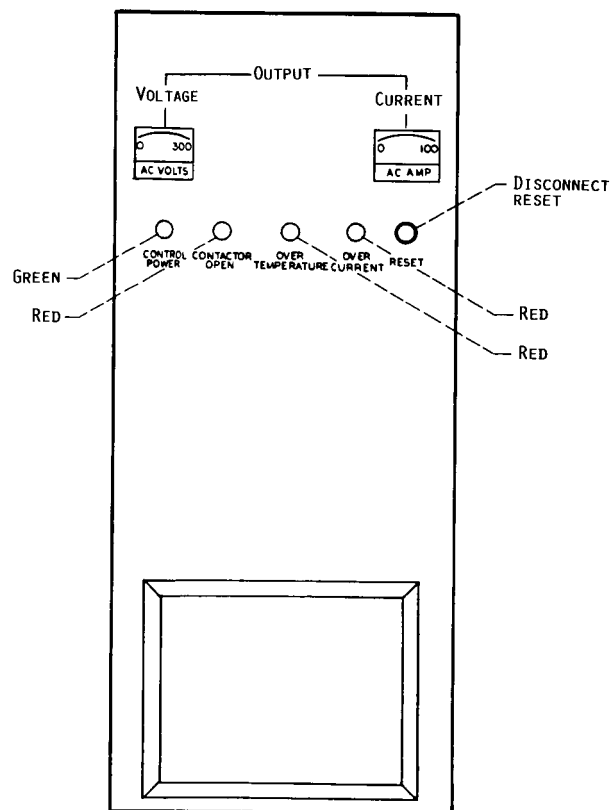


FIGURE 15.- POWER CONDITIONING UNIT.
SHOWN ARE INSTRUMENTS AND INDICATORS
ON DOOR OF DECC INVERTER MODEL 61313.

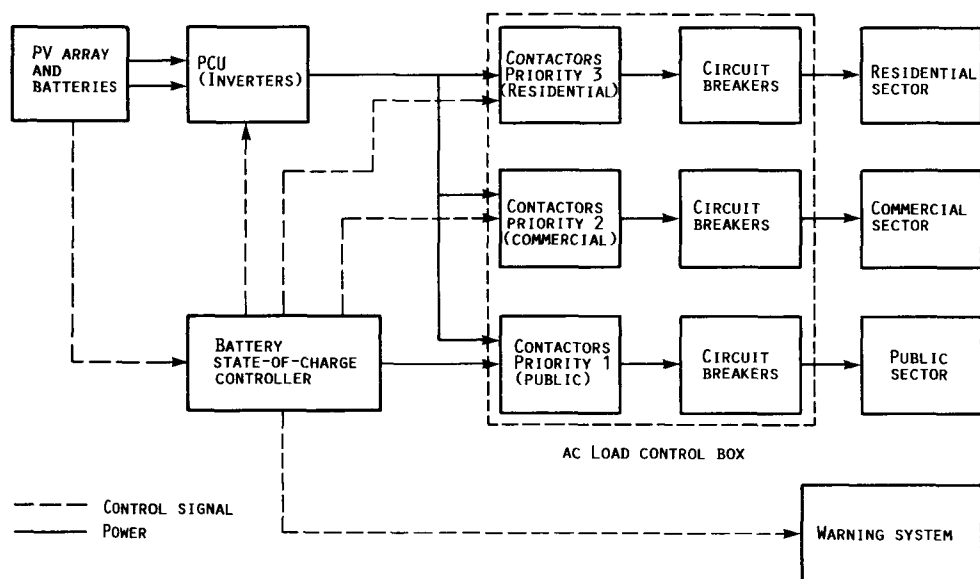


FIGURE 16.- VILLAGE POWER DISTRIBUTION BLOCK DIAGRAM.

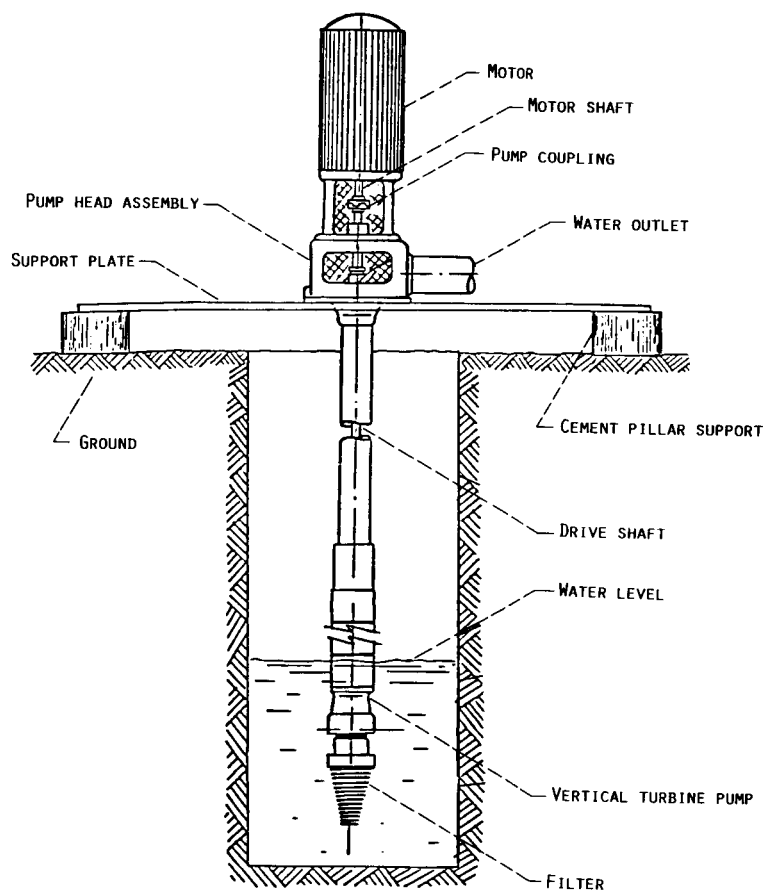


FIGURE 17.- VERTICAL TURBINE PUMP.

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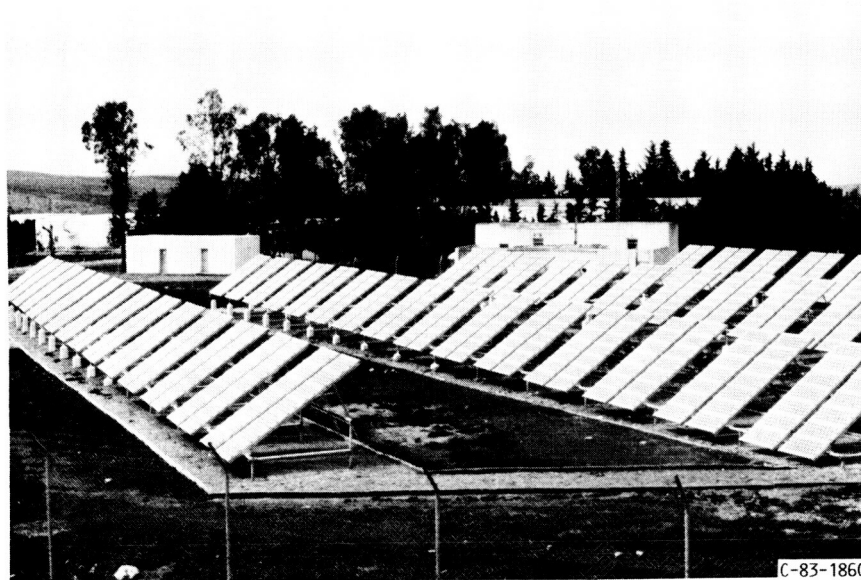


FIGURE 18. - PHOTOVOLTIC ARRAY FIELD, 27 kW_p VILLAGE POWER SYSTEM.

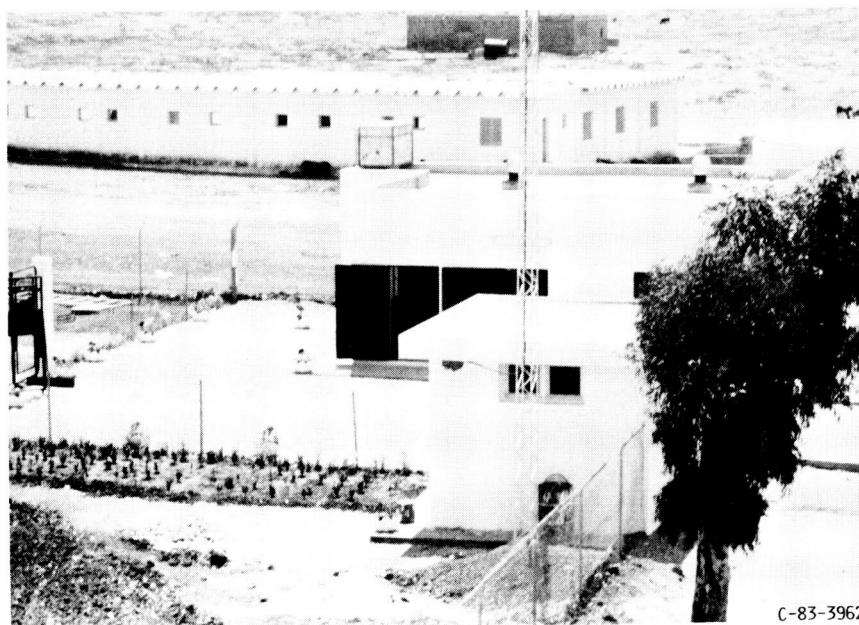


FIGURE 19. - BATTERY AND CONTROL BUILDING.



FIGURE 20. - THE 1.4-kW_p STAND-ALONE PV SYSTEM FOR FARMHOUSE.



FIGURE 21. - THE 1.4-kW_p PV-POWERED WATER PUMPING SYSTEM FOR ORCHARD IRRIGATION.

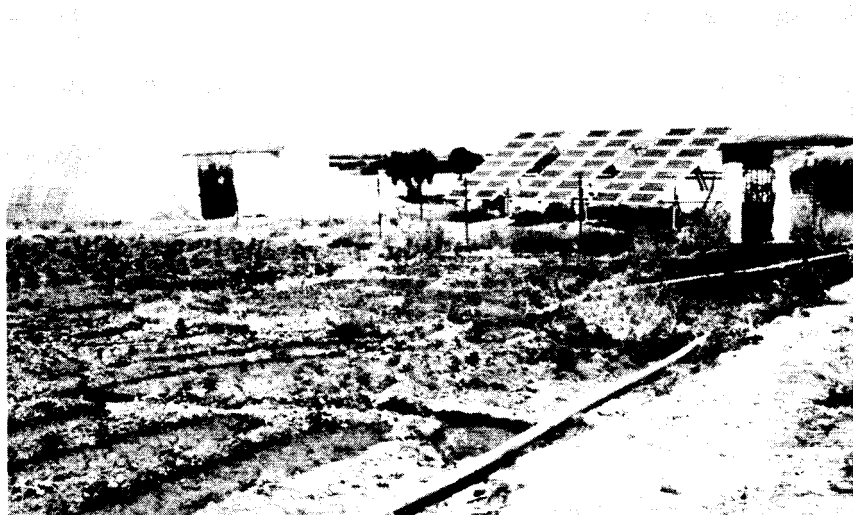


FIGURE 22. - THE 1.4-kW_p PV SYSTEM FOR GREENHOUSE.

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| 16. Abstract In 1979, the Agency for International Development (AID) initiated a renewable energy project with the Government of Tunisia to develop an institutional capability to plan and institute renewable energy technologies in a rural area. The specific objective of the district energy applications subproject was to demonstrate solar and wind energy systems in a rural village setting. The NASA Lewis Research Center was asked by the AID Near East Bureau to manage and implement this subproject. This report describes the project and gives detailed descriptions of the various systems. | | | | | |
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